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THE NAL MAIN RING AS A 15-GEV ELECTRON-POSITRON STORAGE AND COLLIDING DEVICE

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Tom Collins[1] suggested the use of the Cambridge Electron Accelerator (CEA) to perform electron-proton scattering experiments at NAL. The idea, as we can see it, is sketched in Figure 1. The electrons are accelerated in CEA up to the energy of 6 GeV; the protons are accelerated in the NAL Main Ring (MR) up to the energy of 400 GeV. In case a low-β by-pass is required to make the two beams collide with each other, the electrons would still circulate in CEA, but the protons could then be made circulating along a closed pattern, which includes, for example, 5 of the 6 MR sections, and the low-β by-pass section which might replace sector D.

Here we want to investigate the possibility of using CEA as injector of electrons and/or positrons in the MR.

Electrons and positrons can be accelerated in different cycles in CEA up to the energy of 6 GeV and then injected in the MR by means of the low-β by-pass section. The electrons, of course, would move in the opposite direction of the protons, and the positrons in the same direction of the protons. It is obvious that in this operation the MR would be excluded to the protons.

During the first part of the experiment, the electrons and the positrons would be stored independently up to an intensity which value is limited by single beam and beam-beam interaction space charge forces.

The RF system, which should be independent of that accelerating protons, would be standing by during the injection and storage process of the two beams.

Once the injection process is terminated, we would have two options: (i) make the two beams colliding at the energy of 6 GeV. In this case, as we shall see, the amount of RF power, which is needed only to compensate the radiation loss, is very low; because, since the very large radius of MR, the radiation loss is also very low. (ii) Accelerate both beams, at the same time, up to the final energy of 15 GeV.

Then the two beams would be made colliding to each other. The collision can take place either in the MR itself or, to increase further the luminosity, in the low-β by-pass section.

Magnetic Guide Field

For an energy of 6 GeV, the injection field should be of about 270 Gauss. This value is rather low compared to the actual 400 Gauss. We assume the quality of the field at 270 Guass is as good as at 400 Gauss, and that we can hold such field constant over a sufficiently long period of time (hours).

At 15 GeV, the field should be of about 670 Gauss. Thus, during the acceleration, the field will raise from 270 Gauss to

670 Gauss, in a way which must be specified, but that depends on the amount of the radiation loss and of the RF power available during the acceleration. Likely, it is possible to ramp the field at constant speed.

RF Accelerating Field

First of all, since the extreme little variation of the beam velocity during the acceleration (from 6 GeV to 15 GeV), the RF system will be operating at constant frequency.

During the injection and storage period, the voltage of the RF will be constant. It will be raised during or before the acceleration; and, finally, it will be held constant afterwards. The initial and final values depend on the amount of the radiation loss and on the energy spread in the beams.

The energy radiated per turn and per particle is[2]

$$eU = 88.5 \frac{E^4}{\rho} \text{ keV}$$

where E is the total energy in GeV and ρ is the bending radius in meters. eU is plotted in Figure 2 versus energy (ρ = 745m). At injection, eU is 154 keV per turn and per particle, and at 15 GeV, is about 6 MeV.

Thus, we believe that a final peak voltage of 10 MeV/turn may be required.

To increase the luminosity, it is convenient to retain the least number of bunches in each beam. Thus, it is advisable that subsequent pulses from CEA are injected on top of each other at the same CEA RF frequency (480 MHz). At the end of the storage of the two beams, the RF frequency should be reduced until a single bunch is formed in each beam. The last frequency should be of about 1.4 MHz (which corresponds to the harmonic number, 28).

Energy Spread and Length of a Bunch

The equilibrium relative energy spread (standard deviation) in the beam does not depend on the RF parameters, but only on the energy of the beam. It is the result of damping and anti-damping effects of the radiation loss. It is[2]

$$\frac{\sigma_E}{E} = \sqrt{\frac{C_q}{J_E \rho}}\ \gamma \tag{1}$$

where $C_q = 3.84 \times 10^{-13}$m and J_E is one of the three repartition factors

$$J_E = 2 + D \qquad D = \alpha \frac{R}{\rho} .$$

D is the dilation factor α increased by the ratio of the gross orbit radius R to the magnetic radius ρ. In the MR it is

$$D = 0.004 \qquad J_E = 2.$$

From (1) we get

$$\sigma_E/E = 1.9 \times 10^{-4} \quad \text{at} \quad 6 \text{ GeV}$$

$$4.8 \times 10^{-4} \quad \text{at} \quad 15 \text{ GeV}.$$

The equilibrium bunch length (standard deviation) in unit of time is[2]

$$\sigma_\tau = \frac{\alpha}{\Omega} \frac{\sigma_E}{E}$$

where Ω is the angular frequency of the phase oscillations. Thus, the bunch length depends on the RF parameters.

It is, after the acceleration,

$$\Omega = \frac{c}{R} \sqrt{\frac{\alpha h}{2\pi E} \sqrt{(eV)^2 - (eU)^2}}$$

where h (= 28) is the harmonic number. If V = 10MV, then $\Omega \sim 800 \text{ s}^{-1}$, and the bunch half length is

$$\sigma_\tau \sim 2 \text{ nsec}.$$

Nevertheless, the energy oscillation damping is rather slow. If T (= 20 μsec) is the revolution period, the damping time is[2]

$$\tau_E = \frac{2E}{eJ_E U} T$$

which is 0.8 sec and 0.05 sec respectively at 6 GeV and 15 GeV. Thus, the RF system must be adequate to capture the 6 GeV beam from CEA which has a relative energy spread[4] of $\pm 10^{-3}$.

Transverse Size of the Beam

The equilibrium transverse sizes (standard deviations) of the beam, σ_x and σ_z, are the combined effect of the focusing field, the damping and the anti-damping nature of the radiation loss.

If we denote by $J_x = 1 - D$ and $J_z = 1$, the other two repartition factors, we have[2]

$$\sigma_x = \sqrt{\left(1 + \frac{J_E}{J_x}\right) \frac{\alpha R \beta_H}{\nu}} \left(\frac{\sigma_E}{E}\right)$$

$$\sigma_z = \sqrt{\frac{J_E}{J_x} \frac{\alpha R \beta_V}{2\nu}} \left(\frac{\sigma_E}{E}\right)$$

where ν is the horizontal betatron tune and β_H, β_V are the usual beta-functions respectively, on the horizontal and vertical plane. The expression for σ_z applies to the case a magnetic field coupling is present, with the effect to turn over the vertical oscillations the effect of the radiation loss in the horizontal plane. This is the maximum value for the vertical size of the beam.

Inserting numbers ($\nu = 20.2$) we have, at 15 GeV,

$$\sigma_x = 0.25 \sqrt{\beta_H} \text{ mm}$$

$$\sigma_z = 0.18 \sqrt{\beta_\nu} \text{ mm}$$

where β_H and β_V are expressed in meters.

Nevertheless, also the betatron oscillations have a slow damping. Their common damping time is[2]

$$\tau_\beta = \frac{2E}{eJU} T$$

where J stays for either J_x or J_z. The damping time is 1.6 sec and 0.1 sec, respectively, at 6 GeV and 15 GeV. Thus, during the capture process in the MR, the beam has initially the same emittance it had in CEA. The emittance values in CEA (6 GeV) are 0.2 mm mrad in the vertical plane and 8 mm mrad in the horizontal plane.[4]

Intensity Limitation

A. Single Beam Space Charge Forces

Since the very large γ, the number N of particles can be stored in one beam is[3]

$$N = \frac{24}{\pi} \frac{g^2}{Rr_o} \gamma\nu \; |\delta\nu|$$

where g is the half aperture (in the MR, g = 2 cm) and $r_o = 2.8 \times 10^{-13}$ cm.
If we take $|\delta\nu| = 0.05$, we have

$$N = 1.3 \times 10^{13}$$

calculated at the lower energy of 6 GeV. Observe that this limit is independent on how the beam is bunched.

B. Beam-Beam Interaction Limit

Assuming a single interaction, head-on, the maximum number N of particles can be stored in the "strong" beam is[2]

$$N = \frac{2\pi \gamma \sigma_z (\sigma_x + \sigma_z)}{r_o \beta_V^*} |\delta\nu|.$$

Asterisk denotes values of β at the interaction point. If the two beams are separated during the storage and the acceleration, by taking $\gamma = 30{,}000$ and $|\delta\nu| = 0.05$, we have

$$N = 2.2 \times 10^{12}.$$

Observe that, in the limit $\beta_V^* = \beta_H^* = \beta^*$, this limitation on the intensity is independent of β^*.

Luminosity

For zero angle head-on collision, and in the case each beam has only one bunch, the luminosity is[2]

$$L = \frac{N^+ N^- f}{\pi \sigma_x \sigma_z}$$

where N^+ and N^- are respectively the total number of positrons and electrons, and f is the revolution frequency. Taking $N^+ = N^- = 2 \times 10^{12}$ and for σ_x and σ_z the expressions calculated before we have

$$L = \frac{10^{33}}{9\sqrt{\beta_V^* \beta_H^*}} \text{ cm}^{-2} \text{ sec}^{-1}$$

where β_V^*, β_H^* are expressed in meters.

If the interaction occurs in one of the long-straight sections, then

$$\sqrt{\beta_V^* \beta_H^*} = 70 \text{ m}$$

and the luminosity is

$$\boxed{L = 1.6 \times 10^{30} \quad cm^{-2}\ sec^{-1}}\ .$$

This value can be increased either with a low $-\beta$ insertion in the MR or making the two beams to collide with each other in the low $-\beta$ by-pass. In this case, a value of 10^{32} cm^{-2} s^{-1} should be easily attainable if $\beta^* \sim 1m$.

CEA to MR Transfer

CEA can accelerate 10^{11} electrons per pulse and has a repetition rate of 60 pulses per second. Thus, the total number of 2×10^{12} electrons can be transferred from CEA to MR in 20 pulses and in about 1/3 of a second.

The number of positrons that can be accelerated at the same time in CEA is much lower, probably 10^8 per pulse. To achieve the same intensity of the electrons, more time is required, but the all-storage process would not take more than a quarter of an hour.

Injection

As we said before, subsequent pulses are to be injected on top of each other. This way of injecting is delicate because it requires the previous pulses to avoid to strike the edge of the inflector.

This point should be investigated in more detail.

Beam Separation

It is advisable to keep the two beams from colliding during the storage and acceleration proces. For this purpose, it is convenient to install pairs of separating electrodes (or bump-magnets) to obtain two different trajectories in the same fashion as done, for example, in ADONE.

The two beams, then, can be made to collide with each other when requested, just by turning off the separation elements (zero-angle collision), or shifting one trajectory with respect to another until the two bunches collide at some angle in the experimental region. For a better separation of the two beams, or for collisions at large angle, it is preferable to operate in the horizontal plane.

Vacuum

An average vacuum of better than 10^{-7} mm Hg is required and a vacuum of better than 10^{-8} mm Hg is required at the interaction regions.

Pairs of clearing field electrodes should also be installed at convenient distances.

Because of the extremely small size of the beam and the relatively large acceptance of MR, the lifetime of the beam is limited essentially by gas scattering, and only a little by quantum energy fluctuations.

What Do We Need?

The following is the list of the main items we need for this project.

1. A 6 GeV, fast cycling, electron/positron synchrotron (CEA ?)

2. A circular tunnel with a diameter of about 80 m to install the accelerator

3. At most, 800 m low-β by-pass

4. A tunnel to install the low-β by-pass

5. Low-β modifications in the MR

6. A new RF system to accelerate electrons and positrons, independent of the actual RF system to accelerate protons.

7. A vacuum system in the range of 10^{-8} mm Hg.

References

1. Tom Collins, private communication (1972)

2. H. Sands, "The Physics of Electron Storage Rings - An Introduction", SLAC-21, November 1970.

3. L. J. Laslett, Proceedings of the 1973 Brookhaven Summer Study, page 324.

4. Catalogue of High-Energy Accelerators, compiled by M. H. Blewett and N. Vogt-Nilsen, CERN, Geneva, rev. November 1971.

FIG. 1

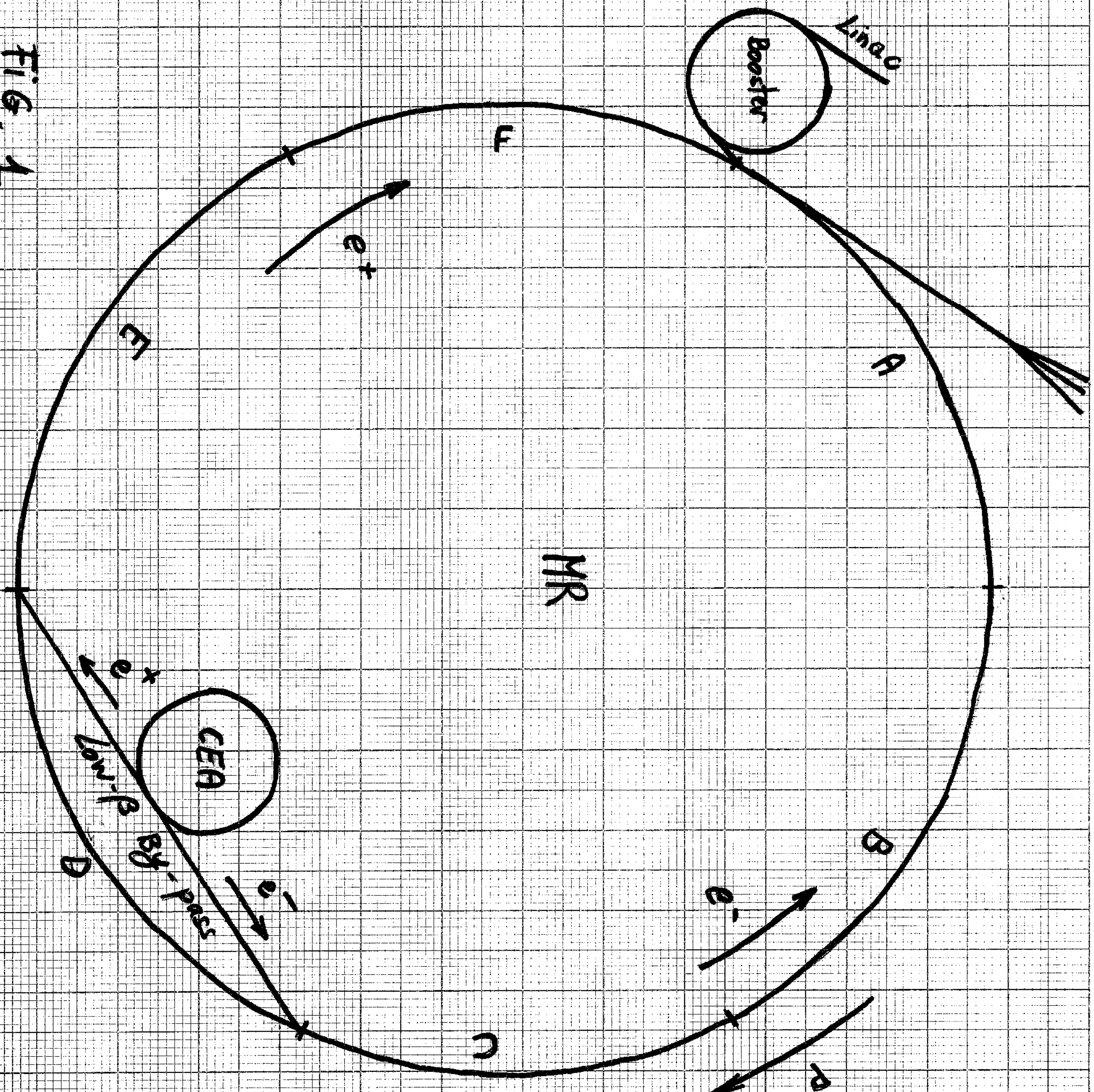

FIG. 1

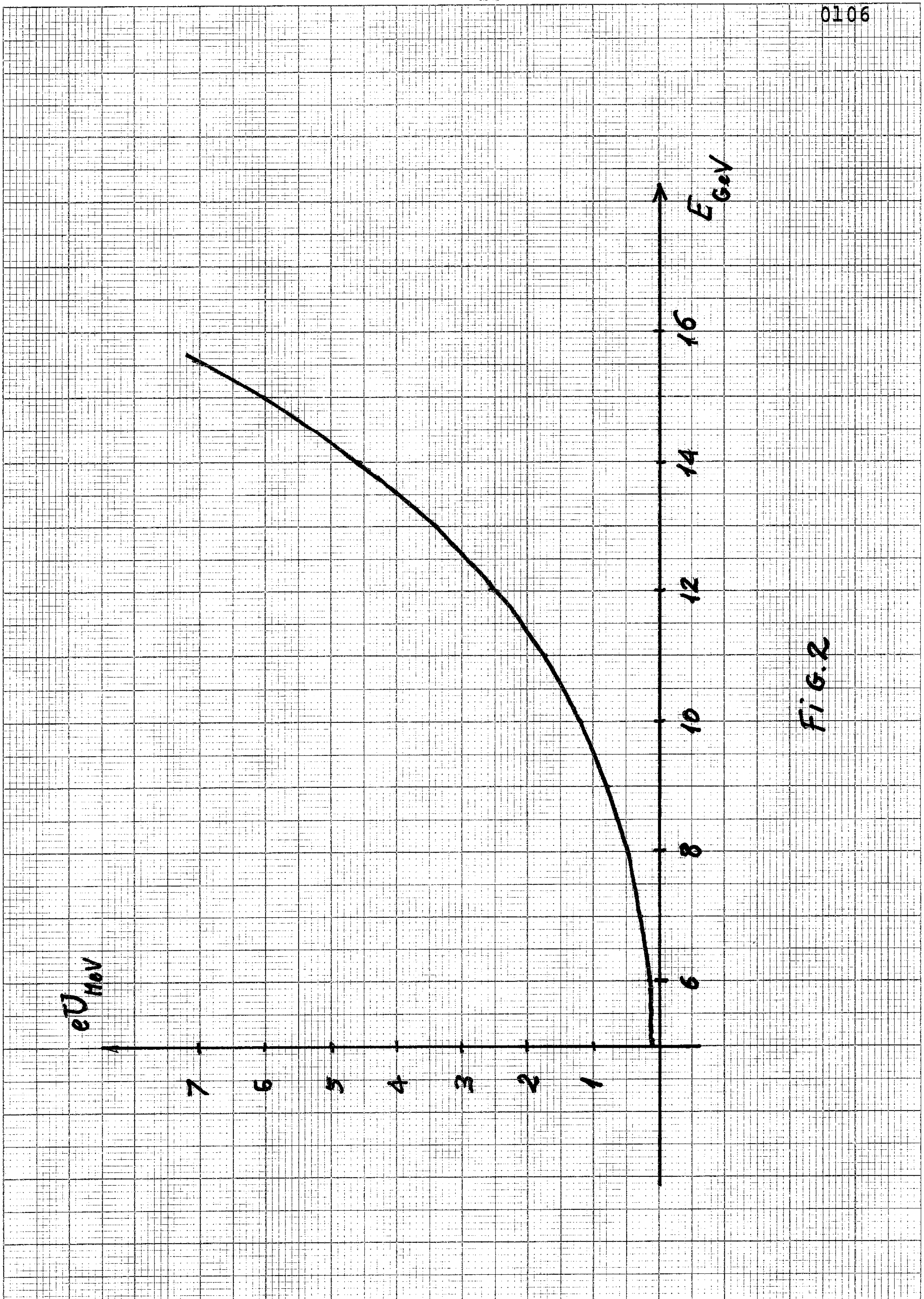

FIG.2